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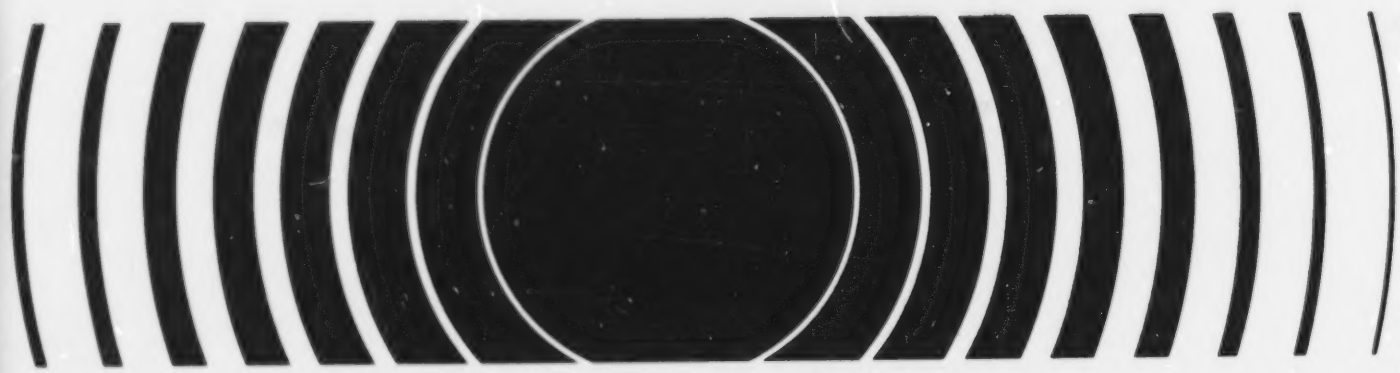

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NEAR-FIELD RADIATION PROPERTIES OF SIMPLE LINEAR ANTENNAS WITH APPLICATIONS TO RADIOFREQUENCY HAZARDS AND BROADCASTING

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June 1978

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PREFACE

The Office of Radiation Programs of the U.S. Environmental Protection Agency carries out a National program designed to evaluate population exposure to ionizing and nonionizing radiation, and to promote development of controls necessary to protect the public health and safety. This report examines some of the radiation properties of transmitting antennas, giving special consideration to the area very near to such antennas which is of most interest when evaluating potential radiofrequency hazards. Readers of this report are encouraged to inform the Office of Radiation Programs of any omissions or errors. Comments or requests for further information are also invited.

Floyd L. Galpin, Director
Environmental Analysis Division
Office of Radiation Programs

ABSTRACT

Analytical expressions for the electromagnetic field have been used to compute electric and magnetic field strengths in the near-vicinity of dipole and monopole transmitting antennas. In particular the fields about a $\lambda/2$ dipole are mapped to illustrate the magnitude and wide variation of field intensity which occurs near the feed point, along the axis of the dipole, and about the tip of the radiating arms. These results are analyzed in terms of evaluating potential radiofrequency hazards which may exist extremely near dipole like broadcast antennas and the aspect of close proximity exposure of maintenance personnel is discussed. The field expressions are used to determine the extent of near-field gain reduction which occurs at distances close to the antenna and this is compared with measured field intensity data taken for a half-wave dipole using a short, nonperturbing field probe. The results for a single dipole are used to model a vertically stacked array of dipole radiating elements used to simulate a typical FM broadcast transmitting antenna. Expected field intensities are then determined for positions close to such radiating structures to assess the potential of biologically significant fields existing about present day FM broadcast installations. It is found that near-field gain reduction can be significant for typically encountered building exposures wherein main beam illumination is possible.

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INTRODUCTION

The Environmental Protection Agency (EPA) currently has under consideration the development of environmental criteria relative to exposure of the general population to radiofrequency (RF) and microwave (MW) radiation. This nonionizing radiation program within EPA has been investigating the problem since 1972. A description of some of the preliminary efforts by EPA at that time have been described by Mills et al., (1971) and Tell (1973).

A continuing effort has been to accurately determine the range of present day RF and MW exposure of the general population in that this environmental data is necessary prior to evaluating the potential biological significance of typically encountered exposures. Such an evaluation is, in turn, requisite to establishing environmental safety criteria.

Numerous investigations of RF and MW field intensities have resulted from the EPA program and have included specific examination of radars (Tell and Nelson, 1974a; 1974b; Tell et al., 1976a; Hankin, 1976; Tell, 1977a), satellite communication earth terminals (Hankin et al., 1974; Hankin, 1974), microwave ovens (Tell, 1978), high frequency emitters (Tell et al., 1974), and broadcast stations (Tell, 1975; Tell, 1974; Tell and Nelson, 1974c; Tell and O'Brien, 1977; Tell, 1978b).

These studies reveal that the most likely contribution to ambient environmental levels of RF and MW radiation is due to transmitters in the broadcast service comprising the various AM,

FM, and television stations. This contention had been previously discussed (Tell, 1972) and has served as impetus for subsequent examination of broadcast fields from the viewpoint that broadcast stations, generally speaking, are our most significant sources of exposure (Tell and Janes, 1975).

An extensive field measurements program since 1975 using a specially developed mobile RF measurement system (Tell, et al., 1976b) has provided extensive environmental data on exposure of the general population to broadcast fields (Janes, et al., 1977a; 1977b; Athey, et al., 1978). These analyses, relying on the environmental measurement data and using computer techniques to manipulate an automated population data base, reveal that the typical median VHF and UHF exposure level of the population in the cities studied by EPA so far is about 0.1 pJ/m^3 electric field energy density or the far field equivalent of 0.007 $\mu W/cm^2$ power density. Figure 1 illustrates the results on population exposure wherein the accumulative fraction of the population in the 10 cities studied exposed to various levels of RF is plotted. It is determined for example that less than 1 percent of the population is exposed to intensities greater than the far field equivalent of 1 $\mu W/cm^2$.

In addition to the information developed on exposure of the population as a whole, data relating to very high RF broadcast fields which can be experienced occupationally have been obtained (Tell, 1976). Another interesting aspect of relatively high intensity broadcast fields is the illumination of tall buildings adjacent to certain VHF and UHF broadcast facilities wherein mainbeam illumination of the building and its occupants is possible (Tell, 1978b). The identification of these hot spots is a continuing effort within EPA and promises to provide added detail on the extent of relatively high RF and MW exposure of various segments of the population.

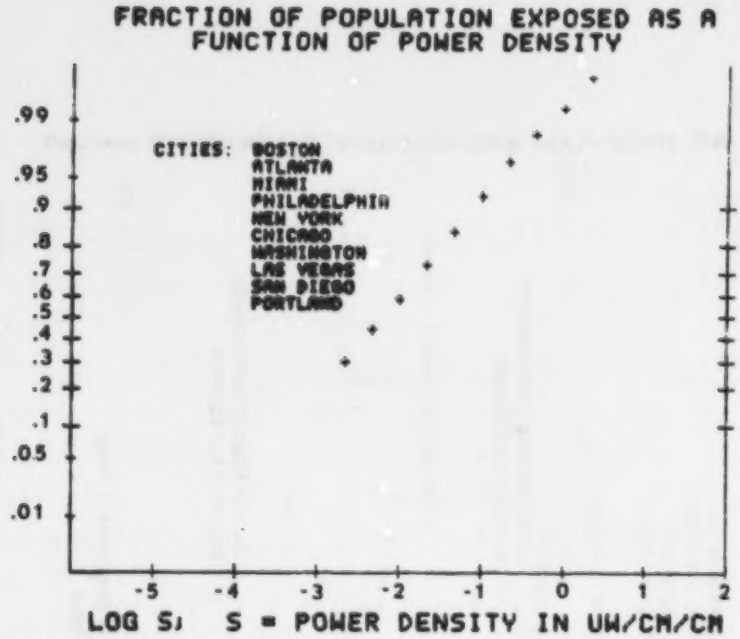


Figure 1. Accumulative fraction of population with exposure $\leq$ the indicated log of the power density.

Fundamental advances, within especially the last three years, in the study of RF and MW dosimetry as it pertains to the human body, have shown that man is not transparent to radiowaves, even at low frequencies. In fact, it is now known that the adult exhibits a whole body resonance phenomena in the range 70-80 MHz wherein the body absorbs significantly more power from incident RF fields than had previously been envisioned. Tell has reviewed this dosimetric development (Tell, 1978c) and Figure 2 illustrates the frequency response of human absorption. It is interesting to note that at resonance the adult body may absorb energy at a rate equivalent to 2.4 times the basal metabolic rate of the resting body when exposed in free space to a field intensity equivalent to the currently accepted RF occupational exposure standard, i.e., 10 mW/cm^2 (OSHA, 1971; ANSI, 1974). Due to rather selective absorption rates of different tissues, the complex inhomogeniety of the internally distributed absorbed power, and physiological

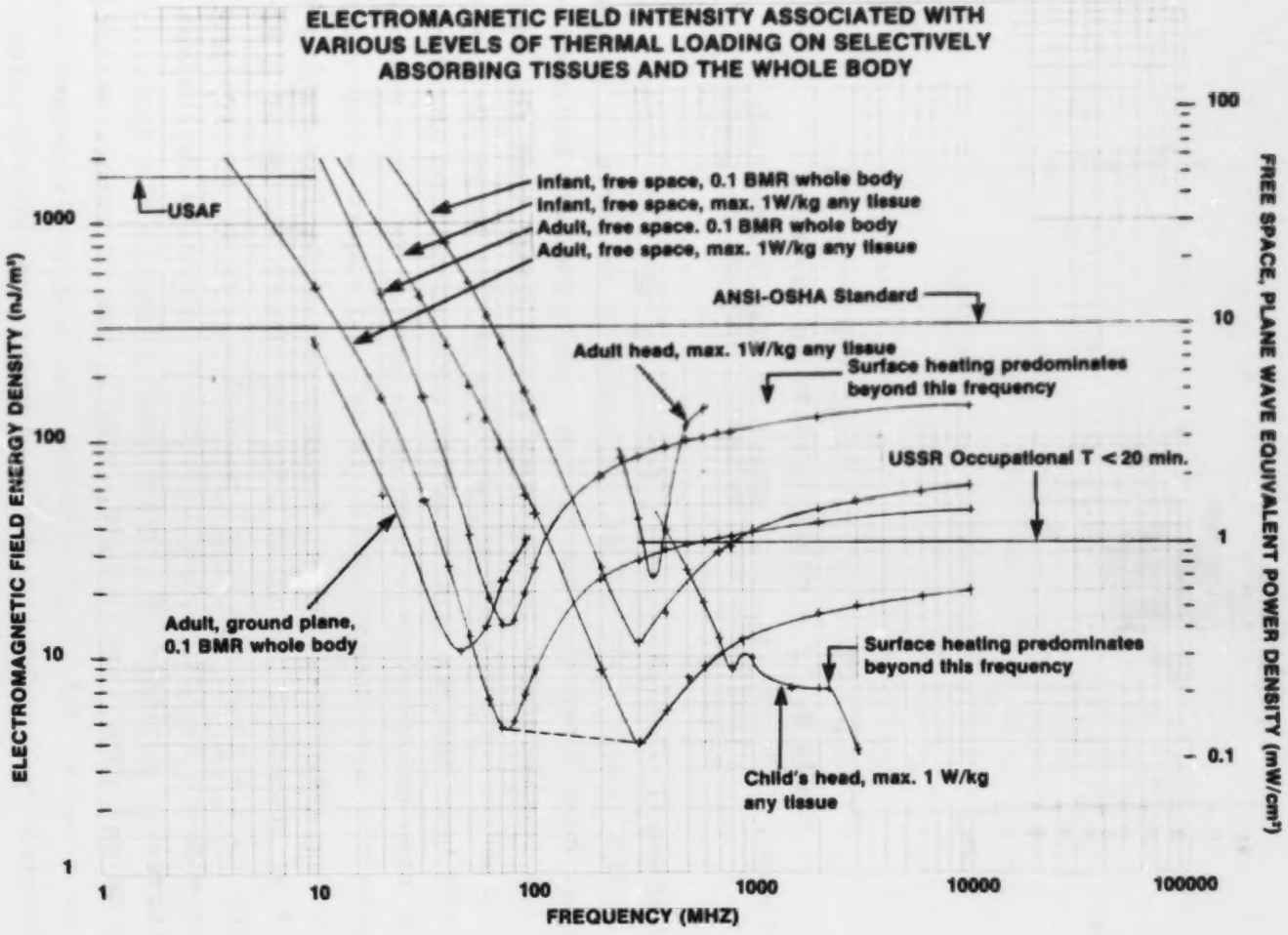


Figure 2. Electromagnetic field intensity associated with various levels of thermal loading on selectively absorbing tissues and the whole body

mechanisms which control heat dispation throughout the body, there is considerable attention presently being given to the reexamination of the OSHA safety standard even for occupational applications (NIEHS, 1977).

Because of the particular resonance frequency found for man and the possible local intensification of energy deposition in specific tissues of between 10 and 30 times the average rate for the body as a whole (Gandhi et al., 1977; Guy et al., 1976) it is of special interest to examine the possibility of high intensity exposure to FM broadcast radiation. This paper presents analytical results obtained on the near-field radiation properties of simple linear antennas in the form of monopoles and dipoles. In particular, the fields about a half wave, tuned dipole are mapped to illustrate the magnitude and variation of field intensity when in its immediate environment. Results are also provided for the local fields around monopoles.

These findings are discussed from the practical aspect of defining hazardous areas near AM and FM radiating structures. Computed values of near field gain for a tuned dipole are presented with additional field measurement data to verify the analytical results. The phenomenon of near field gain reduction is then examined from the viewpoint of using the results to predict the exposure fields in buildings, or any area, immediately adjacent to VHF and UHF broadcast antennas. Where possible, field measurement data is used to supplement the analytical results for array near field gain reduction.

FIELDS OF A DIPOLE

Figure 3 dipicts the geometry used to calculate the electric and magnetic fields near a dipole. Field equations describing the electromagnetic field near such a radiator have been taken from Jordan and Balmain (1968) and are given here.

$$E_z = -j30I_m\left(\frac{e^{-j\beta R}}{R} + \frac{e^{-j\beta R}}{R} - 2\cos\beta H\,\frac{e^{-j\beta r}}{r}\right) \quad (1)$$

$$E_y = j3I_m\left(\frac{Z-H}{y}\,\frac{e^{-j\beta R}}{R} + \frac{Z+H}{y}\,\frac{e^{-j\beta R}}{R} - \frac{2Z\cos\beta H}{y}\,\frac{e^{-j\beta r}}{r}\right) \quad (2)$$

$$H = \frac{j30I_m}{\eta y}\left(e^{-j\beta R} + e^{-j\beta R} - 2\cos\, He^{-j\beta r}\right) \quad (3)$$

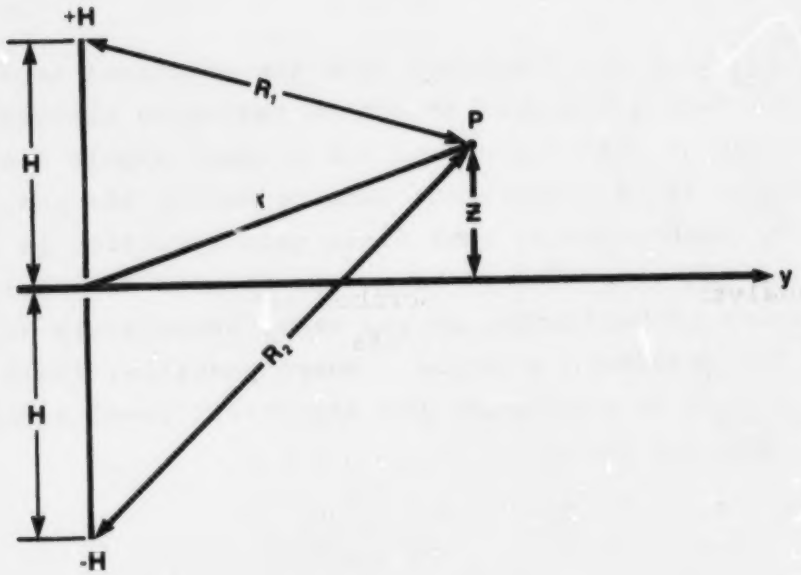


Figure 3. Geometry for computation of fields of a dipole.

E_z and E_y are the parallel and radial components of the electric field originating from the dipole and H is the magnetic field. η is the intrinsic impedance of free space or $120\pi\Omega$. I_m is the maximum loop current along the radiator which is assumed to be sinusoidal in its distribution. A computer program was written which takes as input the frequency, the diameter of the radiating arms of the dipole, their length, and the RF power delivered to the antenna at its feed point. A relation between the RMS transmitter output power and the current on the antenna was obtained by finding the feed point impedance of the dipole using a method developed by Schelkunoff (1943). Because the RMS input power is used in the procedure all fields are determined to be RMS fields. For the purposes of this analysis it has been assumed that all of the transmitter power is effectively delivered to the antenna. In the case of short, non resonant antennas, considerable difficulty in obtaining the required impedance matching and in actuality being able to deliver all available transmitter power into the antenna is encountered.

It is instructive to explore the nature of the fields very near to a dipole antenna and in particular look at the variation in electric field as a function of distance from the antenna. Using the analytical approach described above, the electric and magnetic fields of a family of dipole antennas, each with different lengths, was computed and are presented in Figures 4 and 5. In this case an RMS input power of 1 watt at 100 MHz was used and the radius of the wire radiator was 10^{-10} m. These results are similar to those obtained by Mills (1966) except that in this instance the data are presented in absolute units of distance and for a specific transmitter frequency and power rather than in a normalized system of power and distance units. It has been the experience of the author that, though some generality is lost in using these results, the use of absolute units provides a keener,

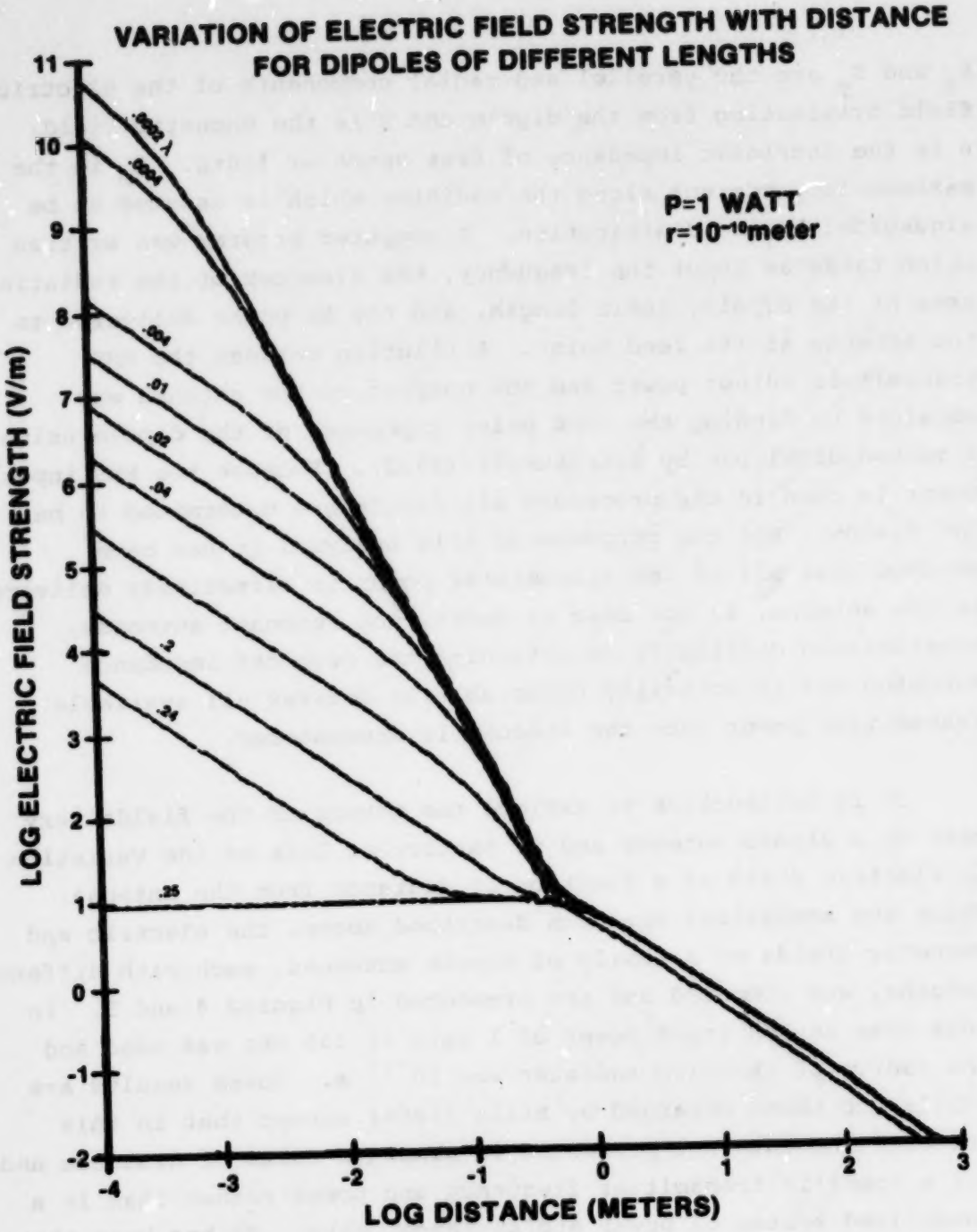


Figure 4. Electric Field Strength vs. distance for dipoles of different lengths

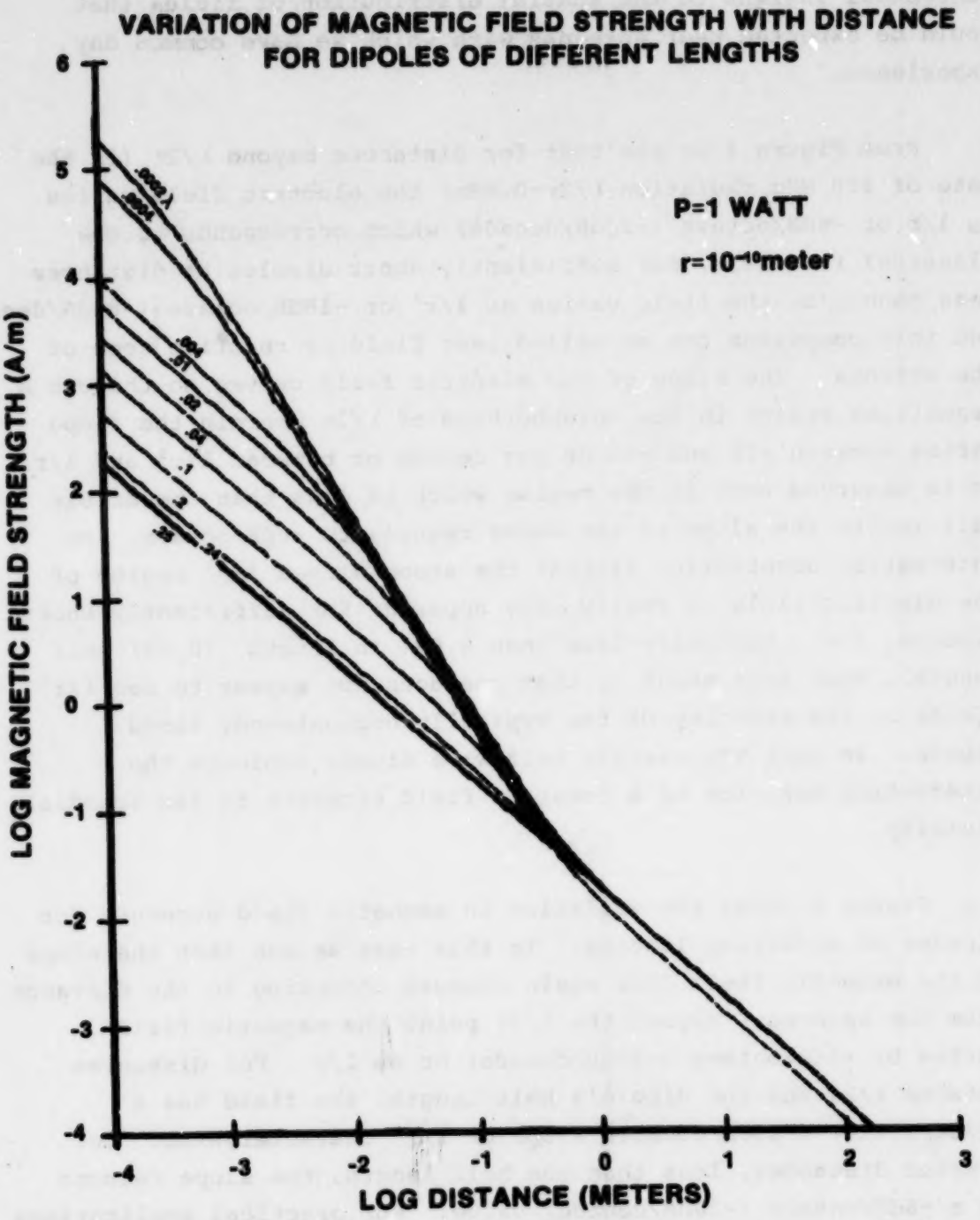


Figure 5. Magnetic Field Strength vs. distance for dipoles of different lengths

conceptual insight to the spatial distribution of fields that would be expected near antennas with which we have common day experience.

From Figure 4 we see that for distances beyond $\lambda/2\pi$ (in the case of 100 MHz radiation $\lambda/2\pi$=0.48m) the electric field varies as 1/r or -6dB/octave (-20dB/decade) which corresponds to the classical far field. For sufficiently short dipoles at distances less than $\lambda/2\pi$ the field varies as $1/r^3$ or -18dB/octave (-60dB/decade) and this comprises the so called near field or reactive zone of the antenna. The slope of the electric field curves go through a transition region in the neighborhood of $\lambda/2\pi$ wherein the slope varies between -20 and -60 dB per decade or between $1/r^3$ and 1/r. It is observed that in the region which is less than the dipole half length the slope of the curve returns to -6dB/octave. An interesting observation is that the steep sloped $1/r^3$ region of the electric field is really only apparent for sufficiently short dipoles, i.e., typically less than 0.08λ in length (0.04λ half length). What this means is that one does not expect to see $1/r^3$ fields in the vicinity of the typically encountered, tuned dipole. In fact the exactly half-wave dipole exhibits the interesting behavior of a constant field strength in its immediate vicinity.

Figure 5 shows the variation in magnetic field strength for dipoles of differing lengths. In this case we see that the slope of the magnetic field line again changes according to the distance from the antenna. Beyond the $\lambda/2\pi$ point the magnetic field varies by -6dB/octave (-20dB/decade) or as 1/r. For distances between $\lambda/2\pi$ and the dipole's half length, the field has a -12dB/octave (-40dB/decade) slope or $1/r^2$ characteristic. For shorter distances, less than the half length, the slope returns to a -6dB/octave (-20dB/decade) value. For practical applications of tuned dipoles we see that one expects the magnetic field to continuously increase until the dipoles surface is reached.

The ratio of the magnitude of the electric field strength to the magnitude of the magnetic field strength is the magnitude of the electromagnetic wave impedance. Figure 6 shows the theoretical variation of the magnitude of the wave impedance of the wave radiating from dipoles of various lengths as a function of distance from the antenna. The dipole is assumed to be in free space having an intrinsic impedance of 377Ω. In the far field the wave impedance approaches the intrinsic impedance of the free space medium. In the near field of short dipoles with half lengths less than about 0.1λ the magnitude of the wave impedance exceeds the impedance of the surrounding medium and increases at a rate of 6dB/octave until the distance reaches a value equal to the dipole's half length. For shorter distances the wave impedance remains constant. This high impedance is characterized as being a high capacitive reactance. The wave impedance decreases as the electrical length of the dipole is made longer. Mills (1966) suggests that a logical boundary between the near and far fields of a dipole is a distance equal to $\lambda/2\pi$. At this point the field intensity curves, electric and magnetic, assume a slope of -6dB/octave and the wave impedance is within about 3dB of the free space value. A significant feature of short dipoles is illustrated by these impedance curves. Very short dipole sensing probes will exhibit a very high wave impedance in their immediate environment and consequently are desireable for use in non-perturbing measurements of field intensity, i.e., they will minimize the load placed on the measured field thereby reducing the error in such measurements. This is particularily important when attempting to make field intensity measurements within the near field of a source wherein the wave impedance of the field is already high (Bowman, 1974; Wacker, 1970).

Field intensity measurements made near the radiating structures of a linear, vertically stacked FM broadcast array have shown that very intense fields exist particularily near the tips of the dipole like radiators (Tell, 1976). This property of electric

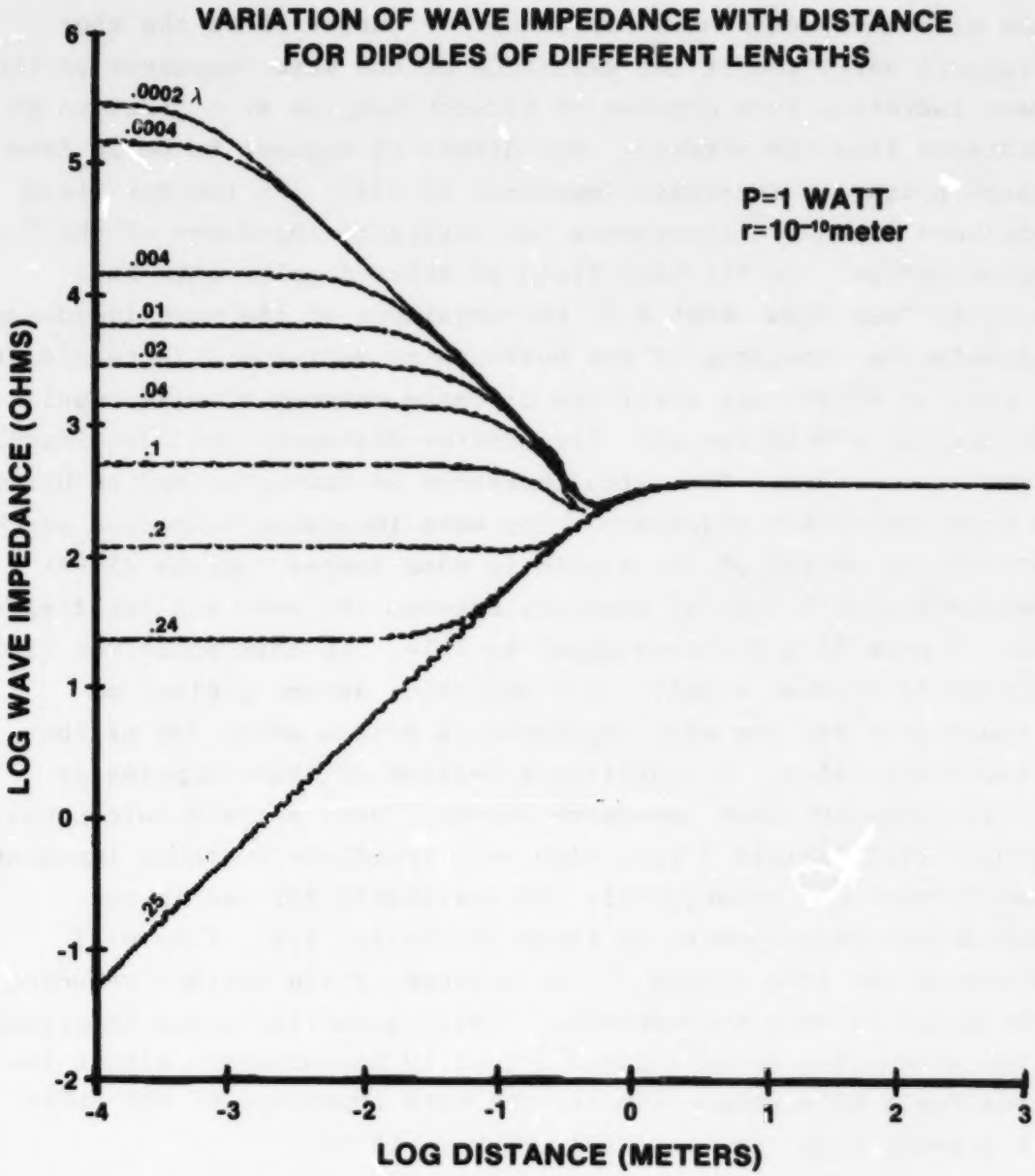


Figure 6. Wave impedance vs. distance for dipoles of different lengths

field like convergence has been examined by using the above discussed analytical formulation and some of the results are given in Figure 7. This figure shows the spatial variation of the magnitude of the electric field in the vicinity of a half-wave dipole antenna driven with 1 kW of power at 100 MHz at five different radial distances from the dipole's center. At a distance of 5m, which is clearly in the far field as seen in Figure 4, the classical far field pattern of a dipole is seen to consist of a figure eight shape wherein the maximum field intensity is observed at points broadside to the dipole, or at 0° in Figure 6, with nulls in the field at points on the axis of the dipole. As the distance from the dipole is decreased to 2m, the electric field increases in amplitude and the pattern begins to broaden with less well defined nulls. At a distance of 1.5m the field pattern is observed to be almost circular. At distances closer than 1.5m the pattern begins to elongate showing the intensification of the local field near the dipole arm tips. At a distance of 0.76m, when at an angle of 90°, the distance to the tip is only 1cm and the electric field is extremely intense.

A circular shaded area in Figure 7 defines the spatial area within which the electric field is less than the ANSI (1974) recommended safe level for RF workers of 194 V/m. Thus, for distances less than 1.5m, or about 5 feet, areas about a half wave dipole radiating 1 kW at 100 MHz will exist in which the ANSI safety standard for indefinitely long exposure is exceeded. This analytical verification of the potential of high fields close in to dipole radiators resonant in the FM band carries a strong implication. Extreme care should be exercised by personnel performing tower work in which they may come into close proximity of VHF broadcast antennas using dipole or dipole-like radiating structures. The local fields about each such structure in a multiple bay broadcast antenna is a function of the power delivered to each bay and stations using relatively low power with small antenna systems may require just as much or more caution than

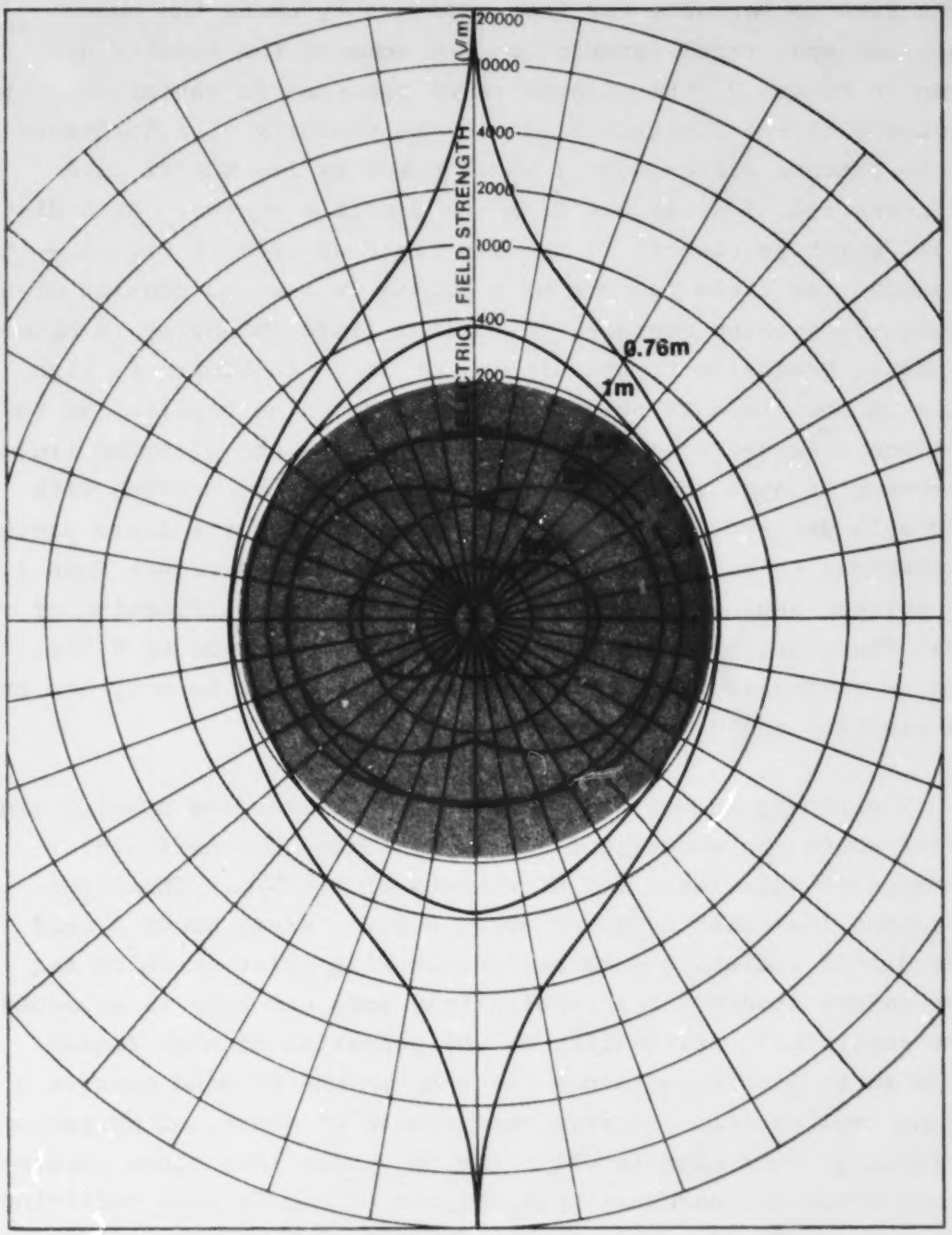


Figure 7. Spatial electric field pattern in the vicinity of a half-wave dipole antenna at five different radial distances, F = 100 MHz

higher power stations using larger antennas. The power per bay is the critical factor in localized fields which may exceed the ANSI safety standard.

Our observation of tower workers routinely working on towers supporting energized broadcast antennas, often times supporting several active antennas, suggests that this common practice merits further attention to minimize or prevent hazardous exposure. Field measurements near a typical FM array showed that localized fields could exceed 18 times the accepted safety standard defined for indefinitely long exposure (Tell, 1976). The ANSI and OSHA standards permit higher field strengths for exposure durations less than 6 minutes. But because of the potentially very intense fields that tower workers might encounter, the permissible duration of exposure is so small that it is questionable whether individuals involved in such situations could maintain their exposure within the allowable limits in view of their limited mobility on a tower.

An area of particular caution involves the use of auxilliary transmitting antennas during times when the main antenna is not being energized. Because auxilliary antennas are often composed of a single bay or substantially fewer bays than the main antenna, the possibility of very high intensities exists in its immediate area. Also, because auxilliary antennas commonly are mounted on the same supporting tower as the main antenna, the possibility of working in the associated high field is increased.

The qualitative implications of this analysis for FM broadcast arrays apply as well to similar considerations for television antennas and the same degree of caution to insure minimizing exposure is required.

FIELDS OF A MONOPOLE

A similar analytical method may be used to investigate the electric and magnetic fields of monopole antennas. This is of some practical significance with respect to evaluating potentially hazardous fields near monopole radiators as used in the AM standard broadcast service. Figure 8 shows the variation in the magnitudes of the electric and magnetic field strengths for monopoles of heights 0.1 and 0.5λ. These two heights define the typically encountered extremes of tower heights found in the AM broadcast service. The calculations assume 50 kW of RMS power are delivered to the monopole since this corresponds to the maximum authorized by the FCC for AM broadcast stations. Furthermore it is assumed that the monopole is driven against a perfectly conducting ground plane; i.e., it is perfectly lossless. Thus these computed field values are conservative in that the finite conductivity of real earth will reduce the actual fields from the computed values. Smith (1969) has examined the effects of finite ground conductivity on monopole fields over a plane earth model. This assumption provides a degree of conservativeness in the predicted field amplitudes. A dashed line in Figure 8 is drawn at the field intensity value that corresponds to both the maximum electric field strength and the maximum magnetic field strength permitted for long time exposure in the OSHA and ANSI personnel safety standards.

It can be seen that for distances less than 10 meters, the field amplitudes will likely exceed the safe levels recommended for frequencies above 10 MHz, this being the lower frequency limit for the present OSHA and ANSI standards. The Air Force (1975) has established a much higher safety limit for Air Force personnel exposure below 10 MHz in view of the significantly

decreased body absorption at these lower frequencies (refer to Figure 2). This higher Air Force standard allows exposure field intensities equivalent to a far field, plane wave of 50 mW/cm^2 power density or a squared field strength value of 188,000 V^2/m^2. The strongest implication of these computed results is that field strengths very near and on the surface of such towers can reach extremely high values and may represent a hazardous condition for workers climbing them while energized with RF.

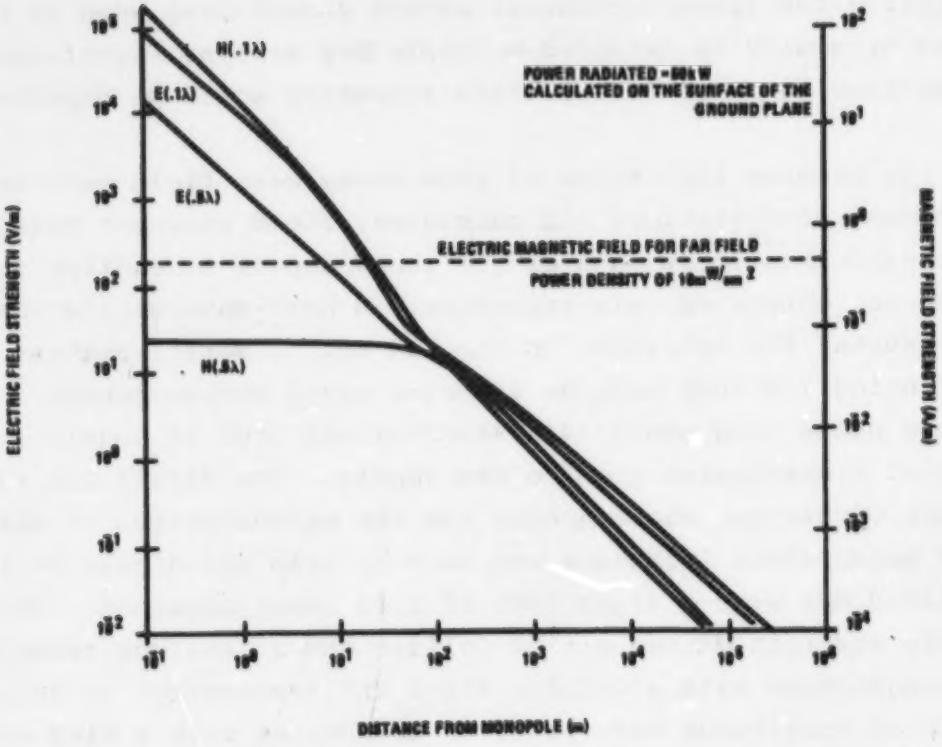


Figure 8. Electric and magnetic field strength in the vicinity of monopoles of common height in the AM standard broadcast service

NEAR FIELD GAIN REDUCTION OF DIPOLE ARRAYS

Recent field measurement data collected by the author in tall buildings situated adjacent to various high power broadcast installations, in particular FM stations, has revealed that the observed field intensity could not, in all cases, be accounted for by the far field specified effective radiated power (ERP) of the station (Tell, 1978c). An investigation of near field gain reduction for linear broadcast arrays showed that when in relatively close proximity to extended multiple bay arrays, significant reductions in the measured field intensity would be expected.

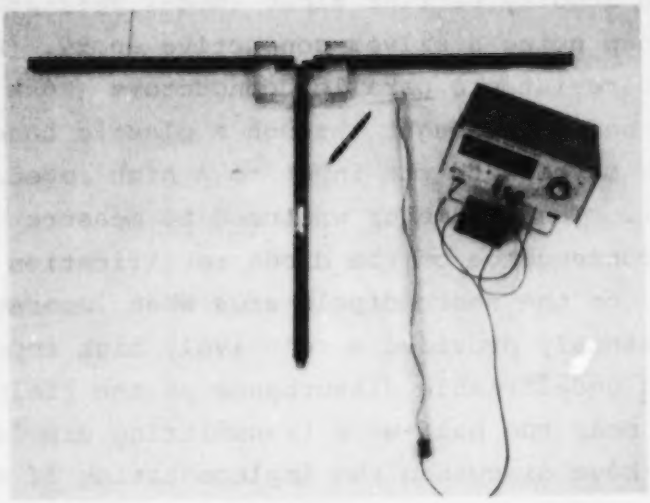
To examine the nature of this array near field gain reduction phenomena, computations and subsequent field strength measurements were performed first on a single tuned dipole to confirm the predicted extent of gain reduction. A half-wave dipole was constructed for operation in the 144 MHz (2 meter) amateur radio band using 7/8 inch outside diameter rigid copper tubing. A sleeve balun (KLM model 144-148-62-N) was used to couple a 50Ω coaxial transmission line to the dipole. The dipole was supported at one wavelength above ground for the measurements. A swept VSWR measurement technique was used to trim the dipole to resonance at 144.0 MHz with a final VSWR of 1.02 being obtained. This dipole was then driven with a Collins KWM-2A amateur transceiver in conjunction with a Collins 62S-1 VHF transverter to deliver 60 watts of continuous wave power as determined with a Bird model 43 thruline watt meter. The watt meter has a specified occuracy of 0.2 dB at an indicated 60 watts. Test transmissions on 144.020 MHz were made using the author's amateur radio license.

A field sensing probe was constructed for the field measurements. This probe consisted of a short (0.0624λ) dipole of 1.6 mm

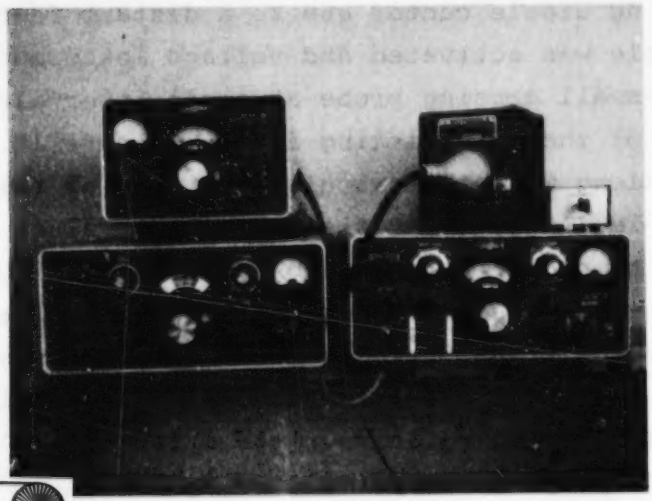
diameter stainless steel tubing (Omega Engineering) with a Hewlett-Packard Schotky barrier diode (model 5082-2800) attached at the center gap using a silver conductive epoxy. At the feed point very high resistance parallel conductors (20Ωk /ft) (Polypenco TFE) were attached and brought through a plastic handle to a connector which mated with the input to a high impedance digital voltmeter (DVM). The voltmeter was used to measure the dc voltage produced as a consequence of the diode rectification of the induced voltage on the short dipole arms when immersed in an RF field. This assembly provided a relatively high impedance probe which minimized undesireable disturbance of the fields which were to be measured near the half-wave transmitting dipole. Free and Stuckey (1969) have discussed the implementation of non perturbing criteria in probe design. Figure 9 is a photograph of the transmitter set up and the high impedance sensing probe.

The transmitting equipment was set up in a vacant parking lot and a fiberglass measuring tape was stretched from the half-wave transmitting dipole center gap to a distant fence some 15m away. The dipole was activated and voltage measurements were made using the small sensing probe at small intervals of distance along the axis of the transmitting dipole. Figure 10 shows the measured data along with the calculated values of relative field for the 2m dipole. Calculated field strength values are for the electric field component parallel to the transmitting dipole. All DVM voltage measurements were normalized to the voltage obtained at 1 meter from the transmitting antenna and then the normalized value obtained for 1 meter was shifted to coincide with the theoretically determined relative field strength at 1 meter. In the range of 20 to 170 cm there is good agreement between the theoretical and experimental values of relative field intensity clearly verifying the reduction in antenna gain at close distances.

Next, using the same rigorous analytical expressions for the electric field of a dipole, computations were performed to determine the resultant electric field magnitude for a vertical array of



144 MHz half-wave transmitting dipole, small field sensing probe (pen points to probe), and DVM



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HF amateur radio transmitter, two meter transverter and dummy load

Figure 9. Experimental near-field gain measurement equipment

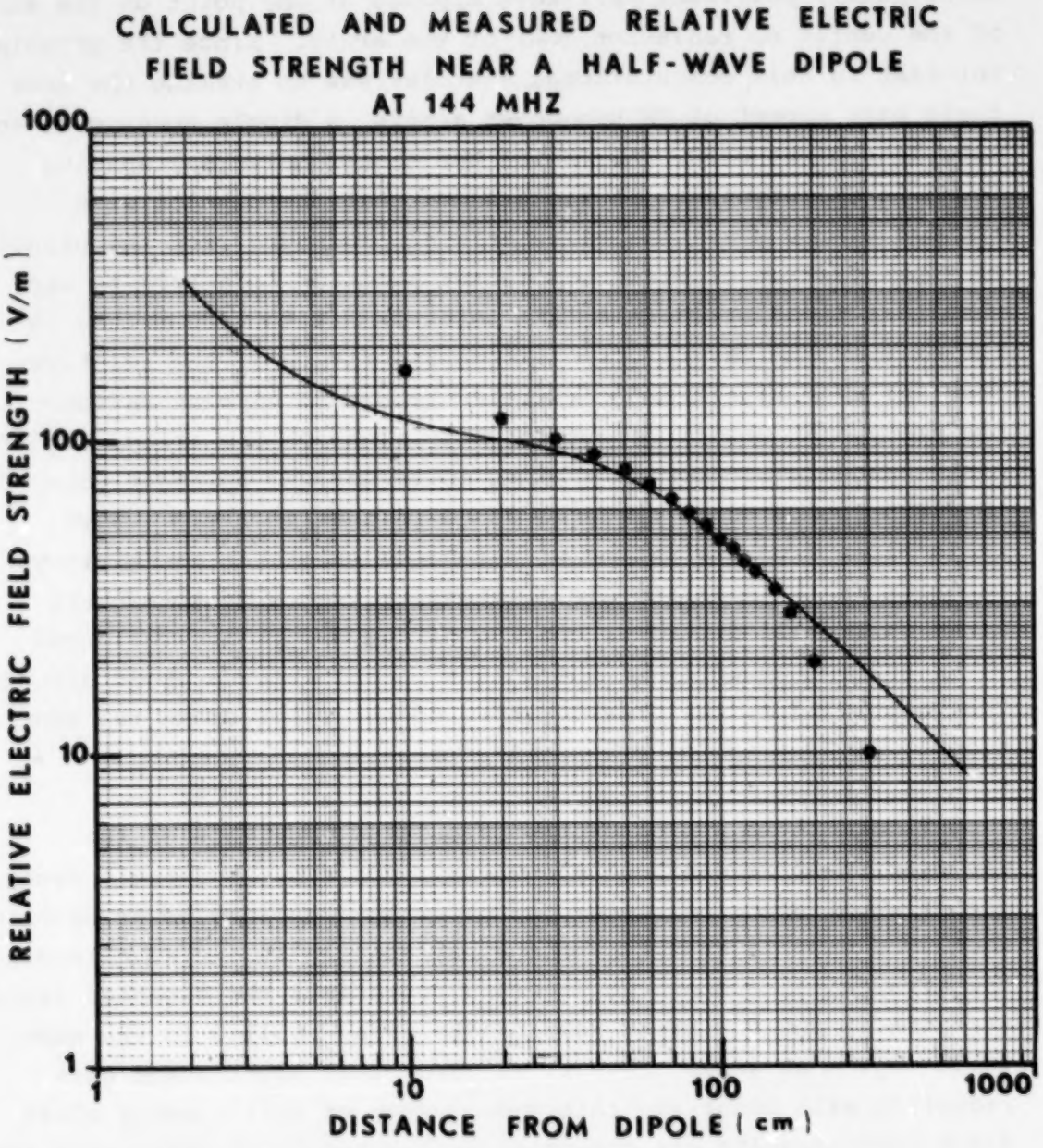

Figure 10. Calculated and measured relative electric field strength near a $\lambda/2$ dipole at 144 MHz

horizontally polarized half-wave dipoles at any point on the axis of the center of radiation (CR) of the array. Since the principle interest in this computational exercise was to examine the near field gain aspect of FM broadcast arrays, a dipole spacing of one wave length was used, this being the almost universal spacing found in FM antennas. It was assumed that the dipoles were excited at 100 MHz. The calculational procedure used the principle of superposition of fields or vector addition to determine the resultant field strength at any point from 1 to 1000 meters on the axis of the CR. A principle consideration is the relative phase of each signal being radiated from each dipolar radiator in the array. At positions sufficiently close to the array, significant phase cancellation occurs tending to reduce the apparent gain of the array compared to the gain found in the far field. Wave reflections from the ground will tend to create an oscillatory behavior in the measured field intensity from a multi-element array which will depend on phasing of the direct and reflected waves and consequently on the height of the antenna above ground. The calculated fields provided here do not incorporate the additional complication of ground effects.

Figure 11 is a plot of the calculated magnitude of the electric field strength on the CR axis for a 12 bay dipole array with 1 kW of power delivered to the array. Uniform power division among the bays is assumed and the bay spacing is one wave-length. The straight line shown in Figure 9 represents the expected field strength if the far field gain of the array applied to the near field region as well. Thus it is clear that significant gain reduction will occur for this model array at sufficiently close distances. Results are presented in Figures 12-20 which give the computed compression of array gain as a function of distance for 2, 3, 4, 5, 6, 8, 10, 12, and 16 bay arrays respectively. In these figures the gain reduction is given directly in decibels below the far field value. These results are similar in appearance

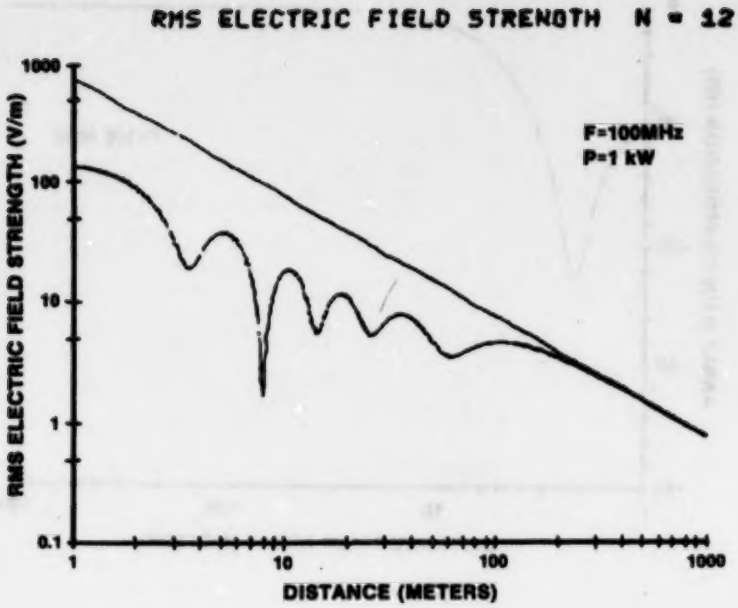

Figure 11. RMS electric field strength vs. distance on the axis of the center of radiation for a 12 bay dipole array with 1λ bay spacing an uniform, in phase power division

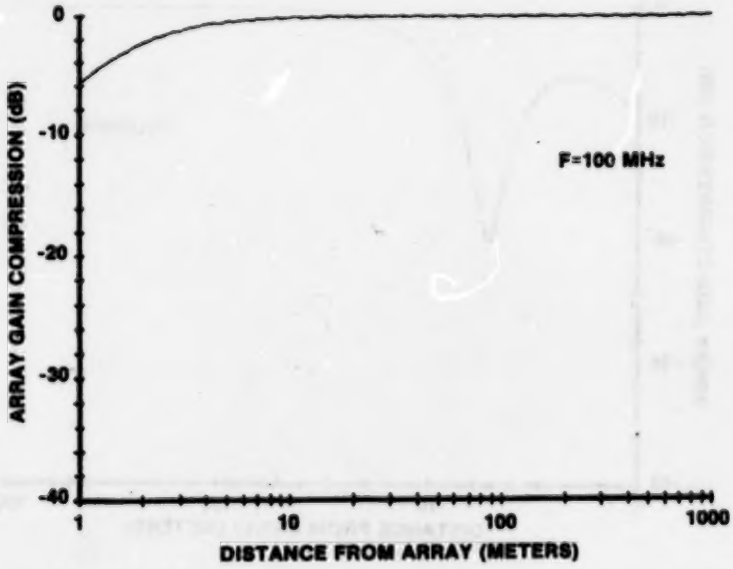

Figure 12. Near-field gain reduction for a 2 bay dipole antenna array operating at 100 MHz with 1λ bay spacing and uniform, in phase power division to each bay

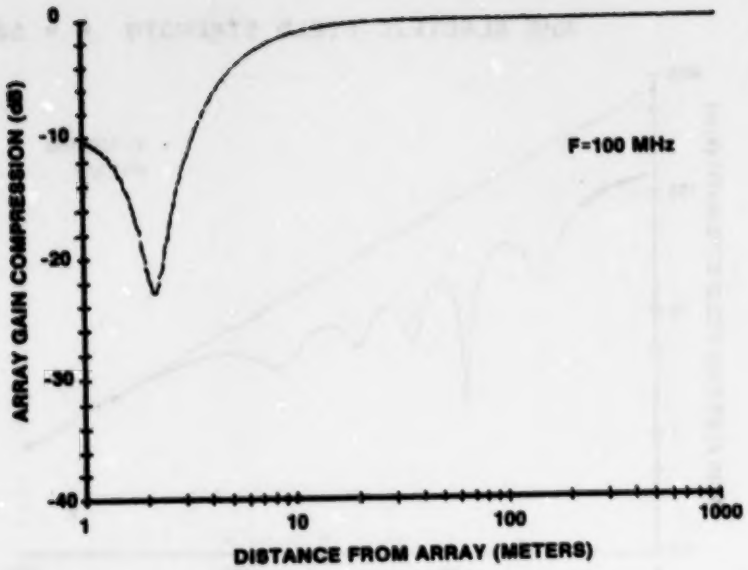

Figure 13. Near-field gain reduction for a 3 bay dipole antenna array operating at 100 MHz with 1λ bay spacing and uniform, in phase power division to each bay

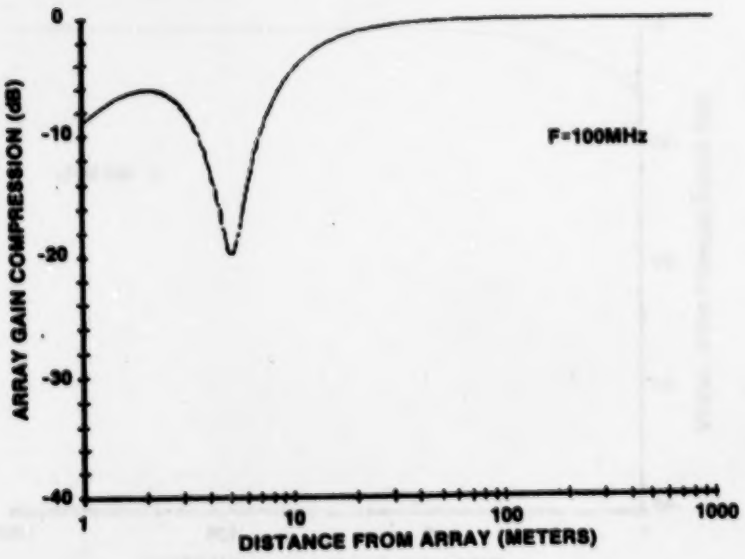

Figure 14. Near-field gain reduction for a 4 bay dipole antenna array operating at 100 MHz with 1λ bay spacing and uniform, in phase power division to each bay

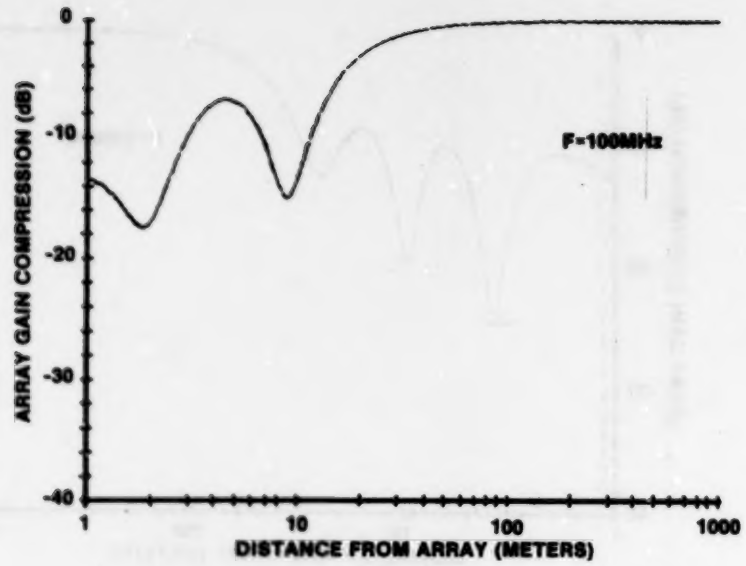

Figure 15. Near-field gain reduction for a 5 bay dipole antenna array operating at 100 MHz with 1λ bay spacing and uniform, in phase power division to each bay

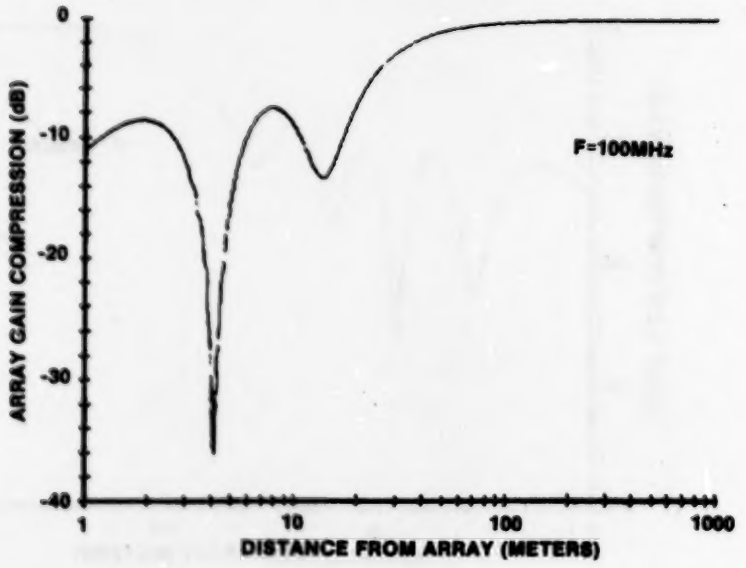

Figure 16. Near-field gain reduction for a 6 bay dipole antenna array operating at 100 MHz with 1λ bay spacing and uniform, in phase power division to each bay

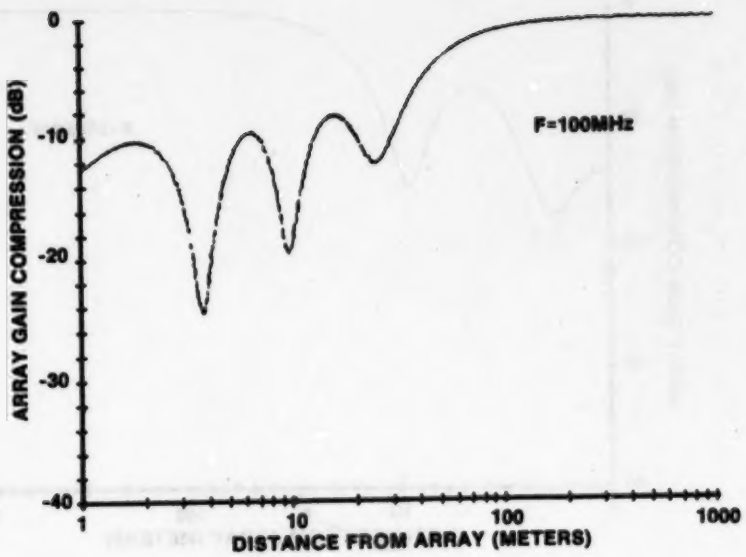

Figure 17. Near-field gain reduction for an 8 bay dipole antenna array operating at 100 MHz with 1λ bay spacing and uniform, in phase power division to each bay

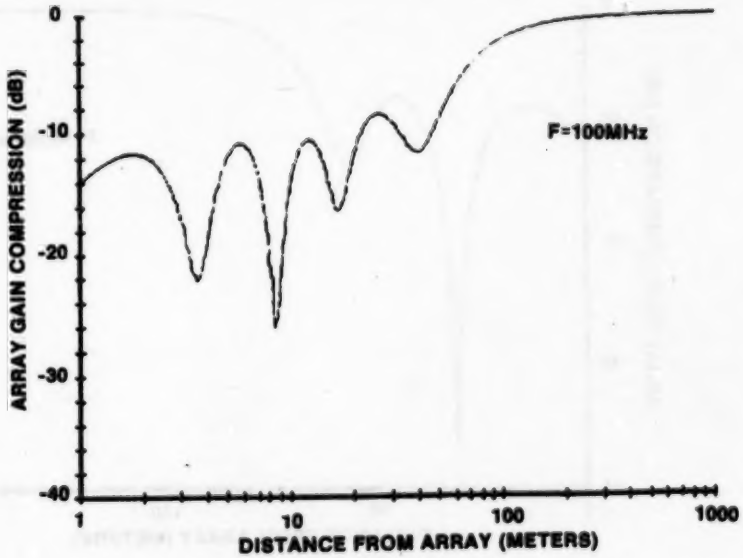

Figure 18. Near-field gain reduction for a 10 bay dipole antenna array operating at 100 MHz with 1λ bay spacing and uniform, in phase power division to each bay

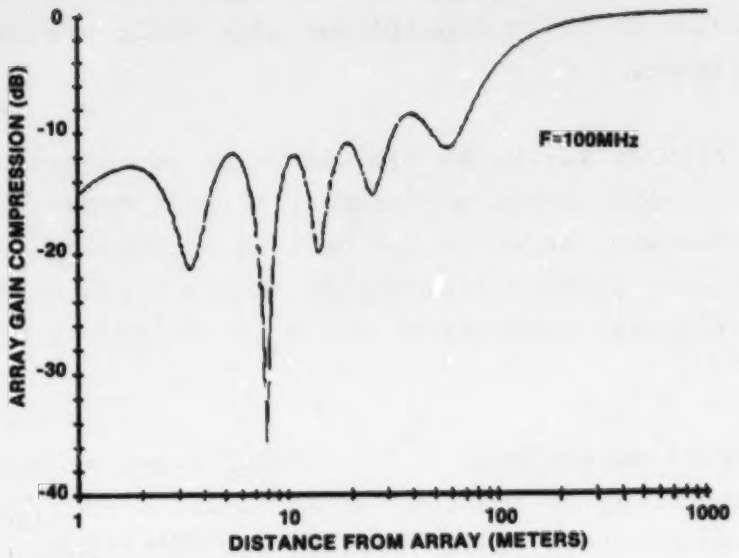

Figure 19. Near-field gain reduction for a 12 bay dipole antenna array operating at 100 MHz with 1λ bay spacing and uniform, in phase power division to each bay

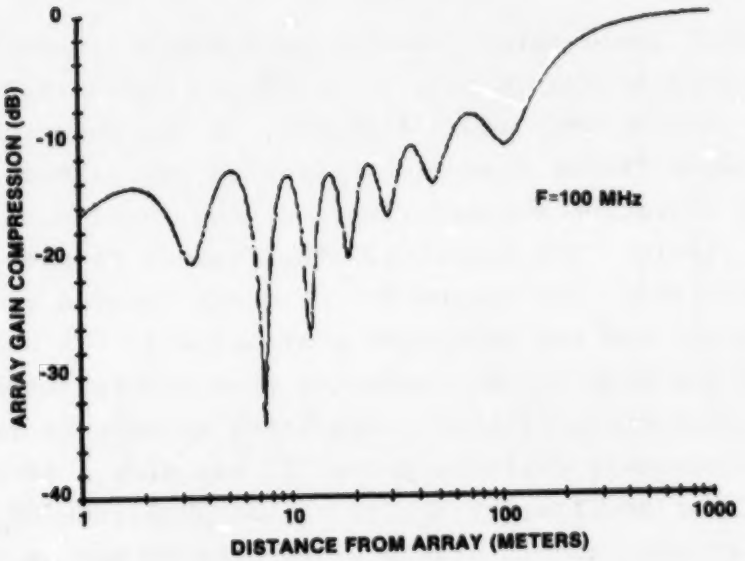

Figure 20. Near-field gain reduction for a 16 bay dipole antenna array operating at 100 MHz with 1λ bay spacing and uniform, in phase power division to each bay

to those obtained for parabolic microwave dish antennas by Cain et al., (1973) in which significant gain nulls are observed at close distances.

From Figures 12-20 the 1dB reduction point has been used to determine an approximate expression, in analytical form, that gives the distance at which the gain is reduced by 1dB. This expression is: $D(m)=-4.7+1.7N+1.2N^2$ where D is the distance in meters to 1dB gain compression and N is the number of bays in the antenna.

A careful measurement of the field intensity near a 12 bay FM broadcast array in Houston, Texas (Tell, 1978c) revealed that the measured electric field strength was significantly below what would be expected on the basis of the far field gain of the array and known transmitter power. Modification of the ERP by reference to Figure 19 resulted in a correspondence within 1dB between measured and calculated values of the field.

The near field gain reduction phenomenon observed for stacked dipole arrays is due, in practical circumstances, i.e., distances greater than about 3 meters, to the phase properties of the individual fields from each radiating bay rather than any near field radiation characteristic of the fundamental radiating structure itself. The practical significance of these findings is that the field intensities in buildings located close by to high power VHF and UHF broadcast stations will not necessarily experience the high fields predicted from simple theory. A detailed examination of the transmitting antenna is required in order to accurately estimate potential exposure. Secondly, because of the oscillatory nature of the amplitude of the fields near such arrays, significantly higher fields may be found in areas farther away than in closer by locations. Thus the field measured inside a large room near a window facing an extended array antenna, may be lower than that measured at a position

substantially farther from the window. Other confounding factors, such as standing wave patterns within such structures, often also tend to distort the observed results.

It should be reemphasized that the computed gain reductions provided in the figures do not take into account the effects of grounds of varying conductivity which will lead to ground reflections and thereby influence the actual field on the axis of the array, usually in an oscillatory manner. These reflected waves will in turn be dependent upon the actual height of the transmitting antenna above ground and will affect the exact near-field gain exhibited by the array. The results, though they do not incorporate ground effects, are provided to illustrate the nature of expected gain reductions but their precision in terms of actual installations will be subject to localized environmental conditions in the vicinity of the transmitting antenna which may introduce significant reflections.

The extent to which these results may be quantitatively applicable to various VHF and UHF TV antennas has not been determined but the qualitative findings of significant gain reduction and the oscillatory nature of the electric field near such arrays are directly pertinent to similar investigations of building exposure. The use of larger numbers of radiating structures, the structures basic similarity to a dipole, and the radiating structure vertical spacing determine the exact form of the associated gain reduction curves for TV antennas.

VERTICAL RADIATION PATTERNS

For several years EPA has observed, in the course of environmental field measurements, that FM broadcast arrays often exhibit extremely strong lobes of radiation straight downward below the antenna. To understand how such radiation can come about, it is only necessary to know the vertical radiation pattern of the basic radiator structure used in the antenna array. If the array, for example is composed of a series of dipoles, horizontally polarized and spaced one wave length apart, the array will exhibit pronounced downward and upward radiation lobes due simply to the isotropic pattern of a dipole in the vertical plane and the adding in phase of signals from all of the bays. To what extent commonly used FM array bay structures may be approximated by a dipole pattern in the vertical plane is not clear. Though such radiation properties are not efficient from a broadcast objective, it appears that some, if not a significant portion of FM broadcast antennas, exhibit this property of emitting a strong "grating" lobe. Others have discussed various techniques for reducing the presence of grating lobes in FM transmitting antennas (Silliman, 1975) and grating lobes have played a significant roll in hazard evaluations of some broadcast installations (Silliman, 1975b; Tell, 1975). A problem in more accurately identifying how common our observations might be is that manufacturers of FM broadcast antennas virtually never make vertical radiation pattern measurements beyond depression angles greater than 30 degrees for practical reasons. Considerations of distant propagation for broadcast purposes commonly entail radiation pattern data only to a few degrees below the horizontal axis of the CR.

Observations of grating lobe effects have not occurred for TV antennas and it must be concluded that the present common use

of one wave length bay spacing and relatively simple radiating structures, which in their own right exhibit relatively significant downward radiation, continue to produce this interesting effect only in some FM antennas.

Calculations have been carried out to determine the relative electric field magnitude as a function of the vertical angle about a dipole antenna array to illustrate the expected grating lobe phenomenon. Figure 21 provides the results for 2, 3, and 6 bay dipole arrays having one wavelength spacing and all bays being fed in electrical phase. Zero degrees represents the direction of the axis of the CR while -90 degrees represents a direction vertically below the transmitting antenna. A basic dipole radiator can be seen to account for significant downward radiation, the angular width of the lobe in fact being greater than the main lobe out to the horizon.

Another method of viewing these results can be used wherein the relative field strength is plotted in a rectangular format rather than a polar format. For a 6 bay dipole array Figures 22 and 23 have been prepared in this rectangular format and illustrate the difference obtained in the vertical pattern under identical conditions except for the bay spacing. Figure 22 is for a one wave length spacing while Figure 23 is for 0.5 lambda spacing. In this case, the even number of total bays, 6, and the half wave length spacing produce a null directly below the antenna, i.e., at 90 degrees. The principle reason for using one wave length element spacing in FM broadcast antennas is the enhancement in far field main lobe gain which can be achieved over 0.5 lambda spacing of close to 3dB. In practice this means that twice as many elements are required to obtain the same gain and consequently the cost of production is essentially doubled.

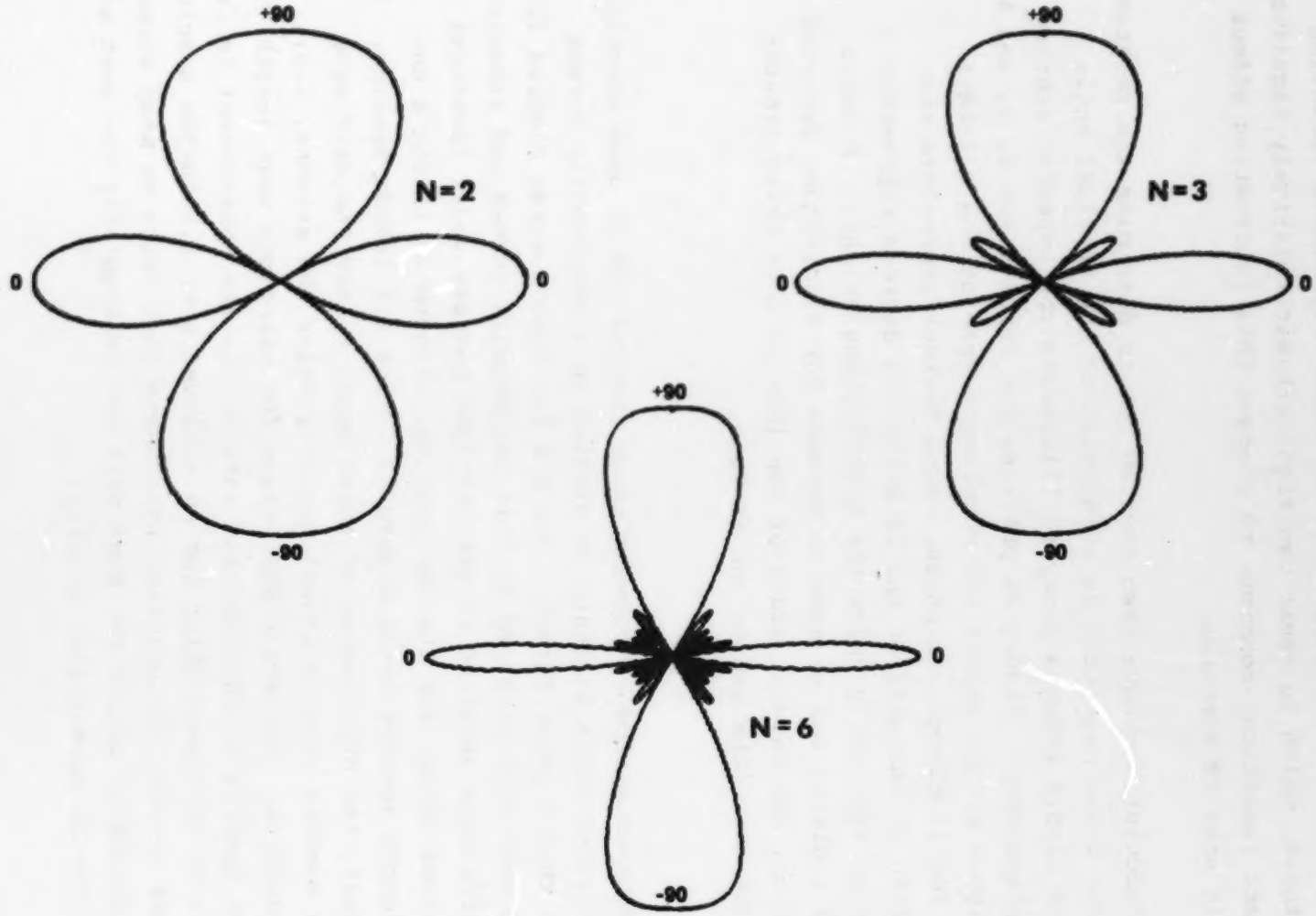

Figure 21. Calculated polar vertical radiation patterns for dipole antenna arrays with 2, 3, and 6 vertically stacked bays spaced 1λ apart and fed in phase with uniform power division

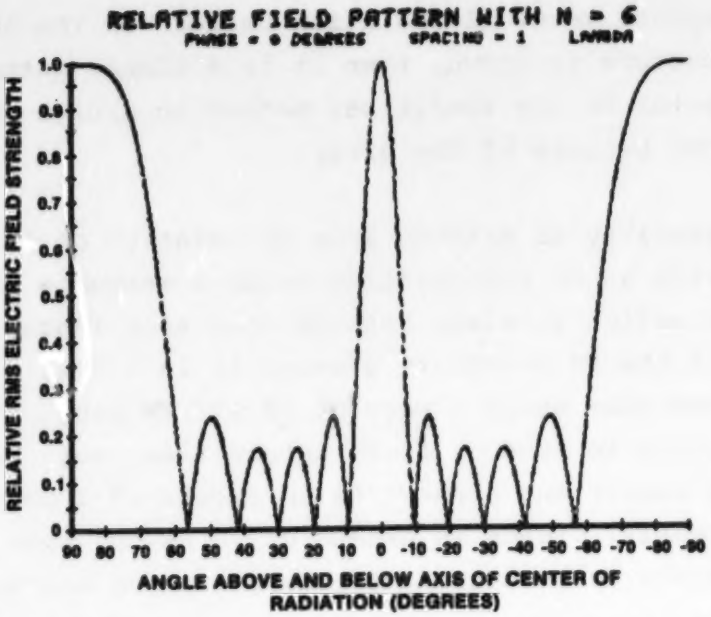

Figure 22. Calculated vertical pattern for a 6 bay dipole antenna array with 1λ bay spacing and uniform, in phase power division to each bay

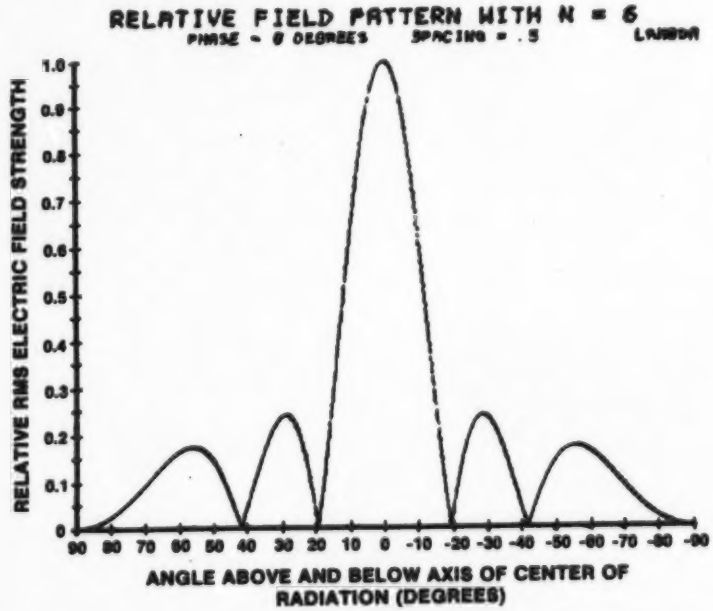

Figure 23. Calculated vertical radiation pattern for a 6 bay dipole antenna array with 0.5λ bay spacing and uniform, in phase power division to each bay

If the actual vertical radiation pattern of the individual radiating structure is known, then it is a simple matter to apply this space factor to the analytical method to arrive at the actual vertical pattern of the array.

The possibility of grating lobe irradiation of the area directly beneath an FM transmitting antenna warrants consideration when evaluating possible hazards near such installations. An analysis of the FM broadcast service in 1975 (Tell and Janes, 1975) indicated that about 3 percent of all FM broadcast stations might be expected to produce field intensities near the base of their antenna supporting structures in excess of 1 mW/cm^2 power density. Recently, fields in excess of 10 mW/cm^2 were actually observed in areas beneath a low-to-the-ground FM station antenna (Tell, 1977b).

SUMMARY

This report has discussed the significant contribution of broadcast stations to radiofrequency exposure of the general population. An analysis of the radiation properties of dipole and monopole antennas has been conducted which illustrates the potentially high radiation fields near broadcast antennas, concentrating on FM antenna arrays, which have been observed in the course of field measurements. Several areas are examined in particular.

The very high field intensities which exist near the active radiators in an FM antenna are deserving of special caution during tower work on energized towers to prevent unsafe personnel exposures.

Secondly, the phenomenon of gain compression within the near field of an antenna array is examined by modeling an FM antenna as a series of horizontally polarized dipoles with uniform power division and equal phasing. It is seen that significant reductions in field strength near the array are expected and have been observed via actual field measurements. The reductions in near field gain are due to the vector summing of fields from the array as opposed to the inherent near field properties of the basic dipole radiator itself. Results are presented for commonly encountered FM arrays which allow estimates of the field on the axis of the CR of the transmitting antenna.

Finally, the presence of grating lobes in some FM broadcast antennas suggests that the fields near the base of FM antenna towers are another area of special concern since relatively intense fields may exist, particularily in the case of antennas mounted close to the ground or on roof tops.

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16. ABSTRACT

Analytical expressions for the electromagnetic field have been used to compute electric and magnetic field strengths in the near-vicinity of dipole and monopole transmitting antennas. In particular the fields about a $\lambda/2$ dipole are mapped to illustrate the magnitude and wide variation of field intensity which occurs near the feed point, along the axis of the dipole, and about the tip of the radiating arms. These results are analyzed in terms of evaluating potential radiofrequency hazards which may exist extremely near dipole like broadcast antennas and the aspect of close proximity exposure of maintenance personnel is discussed. The field expressions are used to determine the extent of near-field gain compression which occurs at distances close to the antenna and this is compared with measured field intensity data taken for a halfwave dipole using a short, nonperturbing field probe. The results for a single dipole are used to model a vertically stacked array of dipole radiating elements used to simulate a typical FM broadcast transmitting antenna. Expected field intensities are then determined for positions close to such radiating structures to assess the potential of biologically significant fields existing about present day FM broadcast installations. It is found that near-field gain compression can be significant for typically encountered building exposures wherein main beam illumination is possible.

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